Analysis of IEEE 802.15.4 MAC under low duty cycle

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Abstract

In this Letter, a discrete-time Markov Chain model is developed to study performance of IEEE 802.15.4 under low duty cycle. The performance is measured in terms of aggregate throughput and average power consumption per packet. The proposed analytical model is verified through ns2 simulations.

1 Introduction

Wireless sensor networks (WSNs) has a wide range of applications in today's world as it is easy to deploy and it is inexpensive. IEEE 802.15.4 can be used as an ideal source of Physical (PHY) and Medium Access Layer (MAC) for WSNs where consumption of energy plays a vital role for the life time of the network. IEEE 802.15.4 was specially designed for network with low data rate and low power consumption [1]. IEEE 802.15.4 gives a very effective and simple solution in context of energy saving as it keeps the nodes in sleep mode when there is no packet to transmit. Beacon enabled slotted CSMA/CA of IEEE 802.15.4 gives further flexibility of using optional inactive period in a superframe to save energy. There are several analytical base studies on the performance of IEEE 802.15.4 available in the literature mostly assuming superframe without an inactive portion [2], [3], [4], and [5]. Recently there are few analytical models developed for IEEE 802.15.4 assuming both active and inactive period in the superframe for saturation conditions [7], [8]. Most of these analytical models were based on the Bianchi's model developed for IEEE 802.11 DCF [6]. Previous works so far found in literature mostly deal with the effect of duty cycle on the network performance. In this Letter, we try to analyze how effective low duty cycle in IEEE 802.15.4 in terms of cost of energy spend per packet both at saturation and non saturation condition. To study the performance we extended the model of [9] and developed a slot based discrete time Markov chain model.

2 Analytical Model

Our model is based on the assumptions and approximations used by [9]. This model is assumed for a beacon-enabled single-hop star topology with a common network coordinator and N identical sensor nodes where all nodes are within the carrier sensing range of each other. It is assumed that the beacon interval has both active and optional inactive period to save energy. Only the uplink data transmission scenario is considered. Frames are assumed to have fixed-L backoff slots and arrive at the nodes according to a Poisson arrival rate of λ frames per second. Accordingly, the frame arrival probability per backoff slot can be derived as-

$$p = \frac{\lambda}{T} \tag{1}$$

where T is the number of available time slots in a beacon interval. MAC level acknowledgment is not considered for the analysis.

3 Node State Model

Fig.1 depicts the CSMA/CA mechanism of an IEEE 802.15.4 sensing node by Markov chain model. As seen from the Fig.1, the Markov chain model is an extension of [9]. In the model T_x, idle and D_f represent the transmission, idle and differed state. T_I be the number of time slots available in the inactive period of a given superframe. For Clear Channel Assessment (CCA), IEEE 802.15.4 requires two consecutive backoff slots to be idle for data packet transmission. Therefore a packet which arrives within the last L+2 slots towards the end of the active period and in the inactive period will be deferred. The probability of a packet deferred P_d, can be calculated as-

$$P_d = \frac{T_I + L + 2}{T} \tag{2}$$

The probability that channel is sensed idle in the first of the two backoff slots is represented by probability p_i^c. $p_{i|i}^c$ is the conditional probability that the channel is idle at the next backoff slot given that it is idle at the current backoff slot. The channel idleness is not considered as independent from one sensing backoff slot to the next. The probability that the channel is sensed idle in a given backoff slot is approximated with the steady state probability of the channel idleness. A node senses the channel to see weather idle in the first of the two backoff slots after every random backoff. The probability that any node begins transmission in a given backoff slot after every random backoff is approximated with the steady state probability p_t^n that a node transmits. The standard specifies the use of a uniform distribution to draw the number of backoff slots that a node has to wait at each random backoff stage. For analytical simplicity, the uniform distribution is replaced by a geometric distribution of the same mean. The transition from the k^{th} random backoff stage of any transmission attempt to the corresponding first carrier sensing stage is characterised by the parameter p_k^n, which is the probability that the node will attempt to sense the channel at the next backoff slot.

A node remains in idle state when it does not have a frame to transmit. On arrival of packet with probability p, a node assures that adequate time slots are there for transmission with probability P_d. If available time slots are inadequate for transmission a packet is deferred to a state D_f. State BO_i, represents the five backoff stages and CS_{ij}, denote the j^{th} carrier sensing backoff slot after the i^{th} random backoff stage where 1≤i≤ 5 and 1≤j≤ 2. On leaving BO_i, a node moves to state CS_{1j} with probability p_i^c to state CS_{2j} with probability $p_{i|i}^c$. If it a node sense the channel idle for two consecutive backoff slot, it enters the transmit state and starts transmitting the packet. At this state channel will be busy for L backoff slots. After random waiting time at each backoff stage and spending one slot each while sensing the channel a node checks availability of time slots with probability P_d. If adequate time slots are available it proceeds to next state or packet is differed to state D_f. $p_{i|i}^c$ can be computed as

$$p_i^c = p_{i|i}^c + p_{i|b}^c(1 - p_i^c) \tag{3}$$

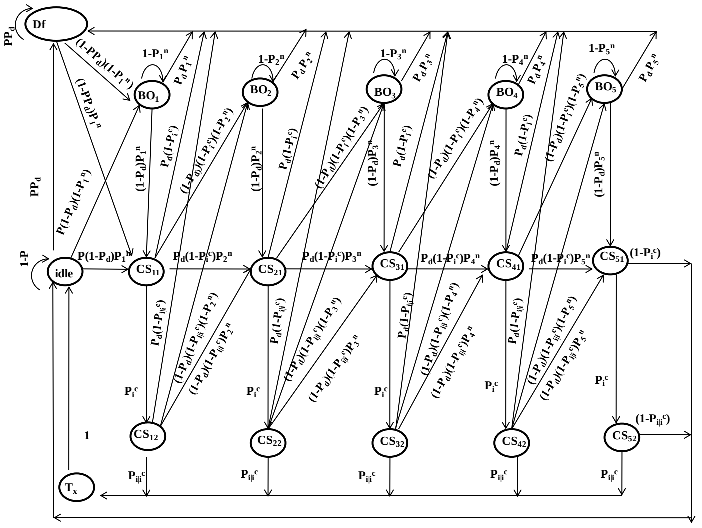

Figure 1: Markov chain model for an IEEE 802.15.4 sensing node

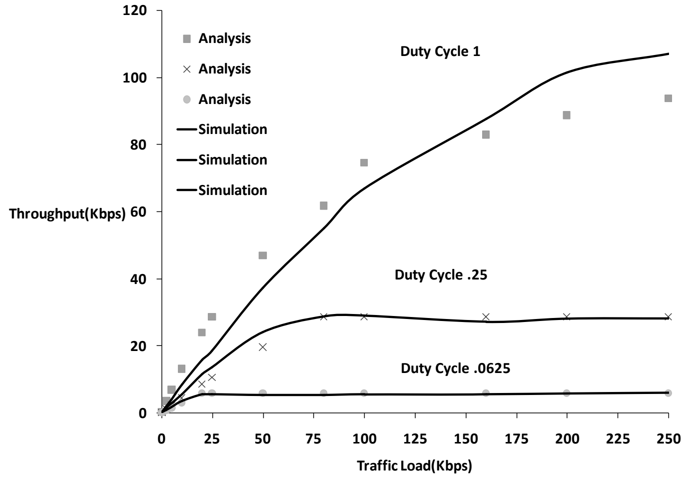

Figure 3: Throughput under different duty cycle at various traffic load

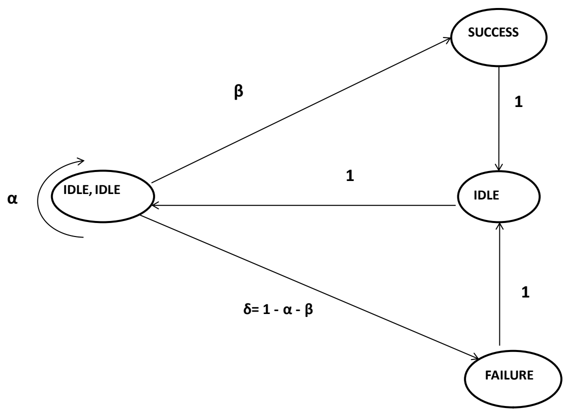

Figure 2: Channel state model for IEEE 802.15.4

$$p^c_{i|i} = \frac{(Lp^c_i - 1 + p^c_i)}{Lp^c_i} \tag{4}$$

$p^c_{i|b}$ is the probability that channel is idle in the next backoff slot given that it is busy at the current backoff slot.

$p^n_t$is the probability that any node would begin transmission in a given backoff slot which can be derived as

$$p^n_t = \frac{p^c_{i|i}(\sum_{i=1}^{5} CS_{i2})}{\pi idle + \pi D_f + \sum_{i=1}^{5} BO_i + \sum_{i=1}^{5}\sum_{j=1}^{2} \pi CS_{ij} + L\pi T_x} \tag{5}$$

4 Channel State Model

To study the behavior of the channel, we adopted the channel state model of [9] as shown in Fig.2. $p^n_{t|ii}$ is the conditional probability of a node transmission provided the channel has been idle for two consecutive slots and can be computed as follows

$$p^n_{t|ii} = \frac{Lp^n_t}{Lp^c_i - 1 + p^c_i} \tag{6}$$

IDLE, IDLE state represents that channel is idle for two consecutive backoff slots and the channel will remain in this state if no node transmits. The probability that no node is transmitting is $\alpha = (1 \text{ -} p^n_{t|ii})^N$. The channel progresses to a SUCCESS state when among N node only one node is transmitting and goes to FAILURE state if more than one node is transmitting at the same time. The probability that only one node is transmitting is $\beta = \text{N}p^n_{t|ii}(1 \text{ -} p^n_{t|ii})^{N-1}$ and more than one at a time is δ = 1-α-β. When the channel is in the SUCSESS or FAILURE state it spends L backoff slots since the length of all packets is assumed to be L backoff slots. At the end of the transmission successful or not, the channel returns to IDLE, IDLE state through an intermediate IDLE state. From the channel state model we can derive the probability of channel idleness for two consecutive backoff slots, p^c_{ii} as

$$p^c_{ii} = \frac{1}{1 + (L+1)(1-\alpha)} \tag{7}$$

By using equation (4) we can compute the probability p^c_i, that the channel is idle at any generic backoff slot.

$$p^c_i = \frac{2-\alpha}{1 + (L+1)(1-\alpha)} \tag{8}$$

5 Aggregate Channel Throughput and Average Power Consumption

The aggregate channel throughput S and average power expenditure E_{avg} is computed as defined in [9].

$$S = \frac{L\beta}{1 + (L+1)(1-\alpha)} \tag{9}$$

$$E_{avg} = (p^n_i - p^n_{beacon} - p^n_{si} + p^n_s)E_s + (p^n_{bo} - p^n_{ir} + p^n_{si})E_{idle} + (p^n_{cs} + p^n_{ir} + p^n_{beacon})E_{rx} + p^n_{tx}E_{tx} \tag{10}$$

E_s, E_{idle}, E_{rx} and E_{tx} are the power expenditure corresponding to transceiver's Sleep, Idle, Receive and Transmit states respectively. To determine average power consumption we consider the Chipcon 802.15.4-complaint RF transceiver, CC2420. The parameters p^n_i ,p^n_s, p^n_{bo}, p^n_{tx} and p^n_{cs} represent the fraction of time spent in Idle, Sleep, Backoff, Transmit and Receive state. p^n_{si}, p^n_{ir} represents the fraction of time spent in sleep to idle and idle to receive state transition. p^n_{beacon} is the frequency of beacon receives.

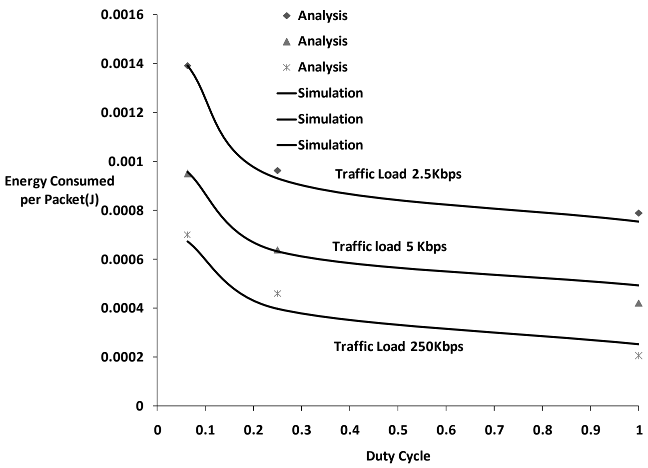

Figure 4: Energy consumed per packet under different duty cycle

6 Model Validation

To validate the model we perform a series of simulated experiments using ns-2.33. We consider a 2.4-GHz PHY layer in which maximum data rate is 250 kbps. Participating nodes in the network is 10. The MAC and PHY header size is 13 bytes along with the data packet payload of 87 bytes. The beacon order (BO) considered is 5 and other MAC parameters are same as their default values define in the standard [1]. The experiments are performed to determine the throughput achieved, average energy consumed per packet of data transfer for the duty cycles 1, 0.25 and 0.0625 at various traffic load. Fig.3 and Fig.4 depicts the comparison between the predicted and simulated results. Fig.3 shows that throughput in an IEEE 802.15.4 network deteriorate quickly with decrease in the duty cycle. As the duty cycle decreases, inactive period increases in the superframe. In a long inactive period, too many packets generated in the inactive period will be buffered. These packets will be transmitted in a burst during the beginning of the next active period, and the collision probability at that time will significantly increase. Low duty cycle decrease the total consumption of energy by putting devices in sleep mode. Low duty cycle save energy at the cost of packet lost and high latency compromising the QoS, so it is crucial to check the amount of energy consumed per packet to estimate its effectiveness. In Fig.4 we see that energy consumed per packet increases with the decrease in the duty cycle. As the duty cycle decreases there is wastage of energy due to sensing and transmission for collided packets and this leads to higher cost of energy in terms of energy per packet.

7 Conclusion

In this Letter on the basis of our analysis, we came to a conclusion that performance of IEEE 802.15.4 MAC lacks in low duty cycle in terms of cost of energy spend per packet. Our future work will be to find an optimal solution so that with the use of low duty cycle we can able to keep intake QoS parameters like energy consumed per packet and latency.

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